Sussing Merger Trees: A proposed Merger Tree data format

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ABSTRACT

We propose a common terminology for use in describing both temporal merger trees and spatial structure trees for dark-matter halos. We specify a unified data format in HDF5 and provide example I/O routines in C, FORTRAN and PYTHON.

Key words: methods: N-body simulations – galaxies: haloes – galaxies: evolution – cosmology: theory - dark matter

INTRODUCTION

The SUSSING MERGER TREES Workshop held in Midhurst, Sussex on 7-12 Jul 2013 brought together tree-code builders from 10 distinct groups: CONSISTENT TREES (Behroozi et al. 2013); D-TREES (Jiang et al. 2014); HBT (Han et al. 2012); JMERGE (Julian Onions, unpublished); LHALOTREE (Springel et al. 2005); MERG-ERTREE (Knebe et al. 2010); SUBLINK (Rodriguez-Gomez et al. 2015); TREEMAKER (Hatton et al. 2003; Tweed et al. 2009); VE-LOCIRAPTOR (Pascal Elahi, unpublished); YSAMTM (Intae Jung etal, in preparation). Unpublished algorithms are briefly outlined in Srisawat et al. (2013).

During that meeting, it was agreed that a common structure was required for recording merger trees, and that it should include both spatial and temporal information. This paper summarises the results of that discussion and sets out the agreed data format. It also presents an HDF5 implementation of that format and describes some example I/O routines that are available to download.

2 THE ANATOMY OF A MERGER TREE

We use and extend the terminology defined in Srisawat et al. (2013). For ease of reference, we repeat that here with appropri-

We start with the basic definition of a halo

• A halo is a dark-matter condensation as returned by a halofinder.

This is a deliberately vague statement as we do not want to be too prescriptive. Halos will usually be identified in the output of a simulation at a fixed time, or snapshot. Halos may be identified at a variety of different overdensities and may be nested within one another (however, we do not allow halos to partially overlap). As the simulation progresses in time, it is natural to associate halos at one snapshot with those in subsequent ones, though that association is

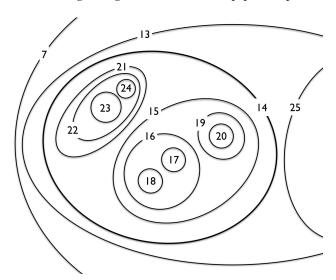


Figure 1. An example of a nested group of halos. The numbering corresponds to that in the spatial structure tree representation shown in Figure 2.

not always obvious and its investigation was the main purpose of the SUSSING MERGER TREES Workshop.

2.1 Spatial structure

An example of a complex set of nested haloes is shown in Figure 1. The numbering of the halos is the same as that in Figure 2 that shows a representation in the form a tree showing the spatial nesting of halos.

During the SUSSING MERGER TREES Workshop it became apparent that the current output structure of halo finders can give difficulties in tree-building. It is common practice to choose one of the haloes in a group and designate it as the 'main halo' (also know as the 'background halo', e.g. Springel et al. 2001). This is fine for undisturbed groups that have a relatively smooth structure with an obvious central halo. However, it does not make sense for the coming together of two (or more) roughly equally-sized haloes for which neither is at the dynamical centre of the group. Instead we propose that all subhaloes be recorded separately, together with an enclosing host halo. Optionally, one of the subhaloes can then be designated a main subhalo of the host. The main halo is then an entity in its own right, rather than being associated with any particular subhalo.

We propose the following nomenclature:

- A spatial structure graph is a set of ordered halo pairs, (H_A, H_B) , where H_A is nested within H_B . It is the purpose of the halo-finding codes to produce a graph that best represents the spatial structure of halos. The halo definition may occur at discrete steps in overdensity, but this is not a requirement.
- ullet Recursively, H_A itself and subhaloes of H_A are **subhaloes** of H_B . Where it is necessary to distinguish H_A from subhaloes that are more deeply nested, the term **direct subhalo** should be used.
- Recursively, H_B itself and hosts of H_B are **hosts** of H_A . Where it is necessary to distinguish H_B from larger hosts, the term **direct host** should be used.
- Optionally, one direct subhalo may be designated the **main subhalo** to indicate that it is at the dynamical centre of the halo.
- The longest continuous sequence of main subhaloes extending (to higher overdensity) from a given halo is known as the **main root**.

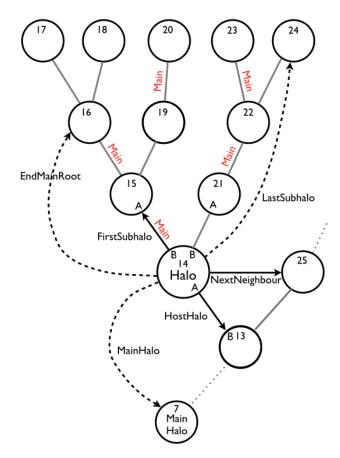


Figure 2. A representation of a spatial structure tree corresponding to the halos shown in Figure 1. The density (size) of haloes decreases (increases) as one moves from top to bottom on the plot. The grey lines show the links of the tree. The A and B labels indicate the ordered pairs that are associted with Halo 14. For that halo, the solid, black arrows show required links in the data structure; the designation of a FirstSubhalo as Main, or otherwise, and the links shown by the dashed, black arrows are optional. Halos 15-24 are subhaloes of Halo 14; Halos 15 & 21 are direct subhaloes.

- A halo that has no host halo is known as a **main halo**.
- A **spatial structure tree** is a spatial structure graph in which there is precisely one direct host for every halo, except for a single main halo.

In Figure 2, halos are represented as circles with IDs as indicated by the number contained within them. The density (size) of halos decreases (increases) from top to bottom on the plot.

Consider Halo 14. It has Subhalos 15-24 of which 15 & 21 are direct subhalos. Halo 15 has been deemed a main subhalo of 14, and Halo 16 a main subhalo of 15, but (for the purposes of illustration) Halo 17 is not at the dynamical centre of halo 16 and so is not designated a main subhalo. Then Halos 14-16 are the main root extending back from Halo 14. In a structure tree, each halo has a single direct host, in this case Halo 13. The outermost enclosing main halo (the main halo) is here Halo 7.

Although not shown in Figure 2, it is also useful to have another link, StartMainRootID that shows the largest enclosing halo of which the halo in question lies on the main root. In the figure,

We use the term root here to distinguish the spatial tree from the temporal one shown in Figure 3 where the equivalent structure is commonly referred to as the main branch.

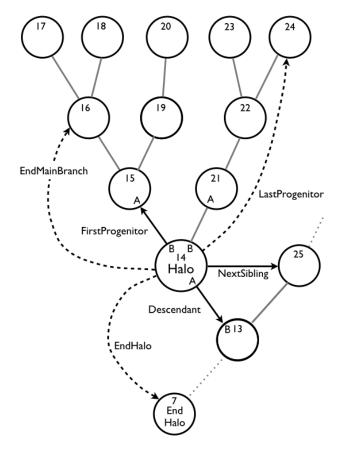


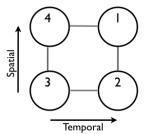
Figure 3. A representation of a temporal merger tree. The lookback time of haloes decreases as one moves from top to bottom on the plot. The grey lines show the links of the tree. The A and B labels indicate the ordered pairs that are associted with Halo 14. For that halo, the solid, black arrows show required links in the data structure; the links shown by the dashed, black arrows are optional. Halos 15-24 are progenitors of Halo 14; Halos 15 & 21 are direct progenitors.

Halo 14 is not a main subhalo of 13, and so Halos 14, 15 & 16 will all have Halo 14 as their StartMainRoot. This makes it easy to decide whether a halo should be considered to be the main component of a larger structure, and if so, which one.

2.2 Temporal structure

The term merger tree was first applied to temporal evolution. As shown in Figure 3, the structure of the temporal merger tree is identical to that of the spatial structure tree, but the nomenclature has been changed to distinguish the two. To maintain flexibility, we have modified the usual definition to make the assignment of a main progenitor optional. To complete the analogy we designate the haloes in the final snapshot (i.e. the end of the simulation) as end halos

- A **temporal merger graph** is a set of ordered halo pairs, (H_A, H_B) , where H_A is older than H_B . It is the purpose of the merger-tree codes to produce a graph that best represents the growth of structure over cosmic time. H_A and H_B are usually taken from adjacent snapshots, but this is not a requirement as there are occasions where haloes lose their identity and then reappear at a later time.
- Recursively, H_A itself and progenitors of H_A are **progenitors**



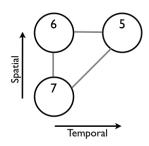


Figure 4. Simple examples of combined structural and temporal merger trees. In each case, overdensity decreases upwards (i.e. enclosing structures) and time towards the right. The left-hand example shows that there is no unique way to traverse the combined tree to reach a particular progenitor subhalo. The right-hand example shows that temporal links may connect a halo to another of differing overdensity (whereas spatial links always connect halos at the same time).

of H_B . Where it is necessary to distinguish H_A from earlier progenitors, we will use the term **direct progenitor**.

- Recursively, H_B itself and descendants of H_B are **descendants** of H_A . Where it is necessary to distinguish H_B from later descendants, we will use the term **direct descendant**.
- Optionally, one of the direct progenitors may be labelled the **main progenitor** this will usually be the most massive, but other choices are permitted. (Note: this deviates from the definition in Srisawat et al. (2013) where the selection of a main progenitor was compulsory.)
- The longest continuous sequence of main progenitors extending back in time from a given halo is known as the **main branch**.
- A halo that has no descendants is known as an **end halo**.
- A **temporal merger tree** is a temporal merger graph in which there is precisely one direct descendant for every halo, except for a single end halo.

2.3 Combined spatial and temporal trees and depth-first ordering

Although our standard does not prescribe it, the trees shown in Figures 2 & 3 are **depth-first ordered** which means that the subhalos of a given halo are all those with indices between FirstSubhalo and LastSubhalo. Similarly, the progenitors are those halos with indices between FirstProgenitor and LastProgenitor.

Unfortunately, there is no straightforward way to order a combined spatial and temporal tree. Consider the left-hand example in Figure 4. Halo 3 can be reached from Halo 1 in two different ways: it is a subhalo of Halo 4 which is a progenitor of Halo 1; and it is a progenitor of Halo 2 which is a subhalo of Halo 1. It would seem, therefore, that we have a choice of making either time or space the inner loop in any tree traversal. As we describe below, however, only the former will allow us to uniquely traverse the tree starting from end, main halos (i.e. the outermost enclosing halos at the endpoint of the simulation) and visiting each halo precisely once.

As one might conceivably want to examine the structure of a halo without knowing its merger history, it would seem natural to preserve depth-first ordering for the former rather than the latter (i.e. make space the inner loop in any tree-search and time the outer one). Unfortunately, that does not work because the progenitors of a main halo can have a variety of overdensities and may contain halos that are at different levels in the same spatial tree. Consider starting a tree traversal from Halo 5 in the right-hand example of Figure 4. Such a search would find Halo 6 as a progenitor of Halo 5 and then

Halo 7 as a subhalo of Halo 6. But it would also find Halo 7 as a progenitor of Halo 5 in its own right and so would appear twice in the tree search.

On the other hand, spatial trees contain halos that are all built from the same snapshot of a simulation and so are coincident in time. So if we search first for subhalos in the final snapshot and then follow all those subhalos back in time, then we will visit each halo precisely once. For that reason, we choose to make space the outer loop and time the inner one within which depth-first ordering is preserved. An example tree-search algorithm (in PYTHON) is given in the Appendix.

3 DATA FORMAT

3.1 Halo indices and pointers

The halos that are returned by a halo finder do not normally have consecutive indices (i.e. with no gaps in the list). However, to allow for efficient data retrieval, the pointer indices that represent the links in the figures need to run in a continuous sequence from HaloIndexOffset to HaloIndexOffset+Nhalo-1, where Nhalo is the total number of halos.² We therefore make this a requirement but also store the original HaloID to allow cross-reference back to the halo catalogue.

To avoid repetition, we describe the structure of the data format here only for the structure tree; that of the merger tree is exactly analogous. To store a basic tree in which there is no main subhalo designation, then all that would be required would be a pointer to the direct host of each halo – this is the HostHaloIndex. However, in order to allow efficient traversal of the tree, we also need an efficient way to locate subhalos of a given halo. That is provided by two pointers: the FirstSubhaloIndex points to the main subhalo, if that exists, or to one of the other direct subhaloes if not (typically that with the lowest halo index). Then each of those subhaloes is also given a NextNeighbourIndex pointer to another of the direct subhaloes (typically the one with the next highest halo index) such that eventually all the direct subhalos have been visited. If any of the halos described above does not exist, then the corresponding pointer is set to a null value (e.g. -1 for C/PYTHON or 0 for FOR-TRAN).

If the halo indexing is done in depth-first order, as shown in the figures, then the (optional) inclusion of pointers EndMainRootIndex to indicate the end of the main root, and LastSubhaloIndex to identify the subhalo with the largest index, allows for efficient identification of contiguous blocks of useful data.

The inclusion of MainSubhaloFlag for identification of the first subhalo as a main subhalo (or not) is also optional. For trees in which the first subhalo is always a main subhalo then this could be omitted. Likewise, it is common practice to always require a main progenitor but the (optional) inclusion of a MainProgenitorFlag allows flexibility not to do so, for example in the case of equal-sized mergers in which there is no obvious dominant progenitor on the previous snapshot.

3.2 HDF5 data format

The use of HDF5 allows for efficient data compression and avoids having to worry about the endianness of the data. Table 1 outlines an HDF5-compatible data format to record both spatial and temporal merger trees. Required entries are entered in plain text and optional ones in italics. The required entries specify minimal information to associate halos with particular snapshots and density levels and to allow efficient traversal of the tree. We also include the halo mass as that is a fundamental porperty that will be required in almost any application.

To increase flexibility, we allow the entries in the MergerTree group to be stored either in a table (one row per halo) or as a set of arrays (one array per property; Nhalo entries per array). Which of these is more efficient in terms of data I/O will depend upon the number of halos and the number of properties that are stored.

Note that the pointers refer to the position of the corresponding halo in this array of halo structures, not to the original halo ID in the halo catalogue (this latter OriginalHaloID may optionally be provided separately to allow cross-reference). The pointers thus have values between HaloIndexOffset and HaloIndexOffset+Nhalo-1, inclusive. A null pointer can be taken as any number that lies outside this range, although the values -1 and 0 are the most common (for C/PYTHON and FORTRAN, respectively).

We give two options for storing the physical properties of halos – in practice users may want to use a mixture of the two. Firstly, for ease of lookup, properties may be specified in the MergerTree group; alternatively, they may be stored by snapshot number in groups Snapshots/Snapshot#. In order to look up the latter a HaloIndex pointer would be needed to identify the appropriate entry in the table.

In general a data-set may contain more than one tree and in that case it may be useful to know the indices of the main (end) halos. Our suggested data structure avoids storing that information as it would be contained in an array of variable length, but we note that it can easily be recovered by searching for haloes for which the HostHaloIndex (DescendantIndex) is the null pointer.

Note that arrays are datasets with a predefined HDF5 datatype. Arrays and attributes can be manipulated using the high-level H5LT routines. Tables have compound datatypes and are manipulated using the high-level H5TB routines.

3.3 Example I/O routines

One of the main advantages of HDF5 and similar formats is that the structure of the file and the nature of its contents can be discerned using utility programs such as hdfview, h51s and h5dump.

To encourage use of the data format described in this paper, we provide example programs to read and write merger tree data files in C, FORTRAN-95 and PYTHON. For those new to HDF5 we strongly recommend first working with PYTHON as the h5py module greatly simplifies the interface with the underlying HDF5 libraries. In applications handling large data-sets, however, the greater efficiency of C or FORTRAN will be required.

We provide some basic examples of merger tree I/O in PYTHON in the Appendix. These routines, together with their equivalents in C & FORTRAN may be downloaded from https://bitbucket.org/ProfPAThomas/mergertree/. These routines are very much work in progress and we encourage anyone with the interest and time to improve and extend them.

² The use of HaloIndexOffset allows for an offset in case that the indexing does not start from zero (e.g. the use of FORTRAN-style indexing, or when working with a subset of a larger data-set).

Table 1. An interpretation of the data format in HDF5.

Group	Object name	Object type	Notes
1			
	Version	Int (32bit) attribute	Version number
	Subversion	Int (32bit) attribute	Subversion number
	Title	String attribute	Title of data-set
	Description	String attribute	Description of data-set
	BoxsizeMpc	Real(32bit) attribute	Comoving box-size in Mpc (not h^{-1} Mpc)
	OmegaBaryon	Real(32bit) attribute	Density parameter of baryons at $z = 0$
	OmegaCDM	Real(32bit) attribute	Density parameter of CDM (excluding baryons) at $z = 0$
	OmegaLambda	Real(32bit) attribute	Density parameter of Cosmological Const. $(w = -1)$ at $z = 0$
	H100	Real(32bit) attribute	Hubble parameter / $100 \mathrm{km s^{-1} Mpc^{-1}}$
	Sigma8	Real(32bit) attribute	RMS linear overdensity at $z = 0$ in spheres of radius $8 h^{-1}$ Mpc
		Attribute	Optional additional attributes
	Snapshots	Group	Snapshot info/data
	MergerTree	Group	Merger tree info/data
/Snapshots			
=	NSnap	Int (32bit) attribute	Number of snapshots
	Snap	Table	Table of snapshot properties (a, t,)
	SnapProp	Table	Table of snapshot property names/descriptions/units
	Snapshot1	Group	Snapshot particle and/or halo data
	SnapshotNsnap	Group	Snapshot particle and/or halo data
/Snapshots/Sn	apshot#		
	NSnapHalo	Int (32bit) attribute	Number of halos in this snapshot
	SnapHalo	Table	Table of halo properties (Mass, Pos, Vel, AngMom,)
	SnapHaloProp	Table	Table of halo property names/descriptions/units
/MergerTree			
Ü	NHalo	<pre>Int(32bit) Int(64bit) attribute</pre>	Total number of halos
	HaloIndexOffset	Int (32bit) Int (64bit) attrribute	Pointer index value of first halo in the Arrays/Tables
	TableFlag	Int (32bit) attribute	0 1 if halos stored in Arrays Table
		•••	Optional additional attributes
Either (table f	format):		
	Halo	Table	Table of halo properties (Snapshot, Density, Mass, FirstSubhaloIndex,)
	HaloProp	Table	Table of halo property names/descriptions/units
or (arrays of s	7		
, , ,	Snapshot	Int(32bit)	Snapshot number
	Density	Real(32bit)	Over-density of halo (units to convert to critical density)
	Mass	Real(32bit)	Some measure of halo mass
	FirstSubhaloIndex	Int(32bit) Int(64bit)	Pointer to FirstSubhalo
	NeighbourIndex	Int (32bit) Int (64bit)	Pointer to Neighbour
	HostHaloIndex	Int (32bit) Int (64bit)	Pointer to HostHalo
	FirstProgenitorIndex	Int (32bit) Int (64bit)	Pointer to FirstProgenitor
	NextSiblingIndex	Int (32bit) Int (64bit)	Pointer to NextSibling
	DescendantIndex	Int (32bit) Int (64bit)	Pointer to Descendant
	EndMainRootIndex	·	Pointer to halo at the end of the main root
		Int (32bit) Int (64bit)	
	EndMainBranchIndex	Int (32bit) Int (64bit)	Pointer to halo at the end of the main branch
	LastSubhaloIndex	Int (32bit) Int (64bit)	Pointer to LastSubhalo
	LastProgenitorIndex	Int (32bit) Int (64bit)	Pointer to LastProgenitor
	MainSubhaloFlag	Int (32bit)	0 1 if FirstSubhalo is a main subhalo
	MainProgenitorFlag	Int (32bit)	0 1 if FirstProgenitor is a main progenitor
	OriginalHaloID	Int(32bit) Int(64bit)	Halo ID in original catalogue
	HaloIndex	Int(32bit) Int(64bit)	Location in Snapshot Halo table
	Pos	Real(32bit) $array[3]^{\ddagger}$	Comoving position of centre of mass
	Vel	Real(32bit) $array[3]^{\ddagger}$	Peculiar Velocity of centre of mass
	AngMom	Real(32bit) <i>array[3]</i> [‡]	Angular momentum of halo
		•••	Other halo properties

[†]Each array to come with string Description and Units attributes. ‡i.e. arrays of size [NHalo,3] or [3,NHalo] dependent upon the ordering of the data (C-like or FORTRAN-like, respectively). Italic text indicates optional entries.

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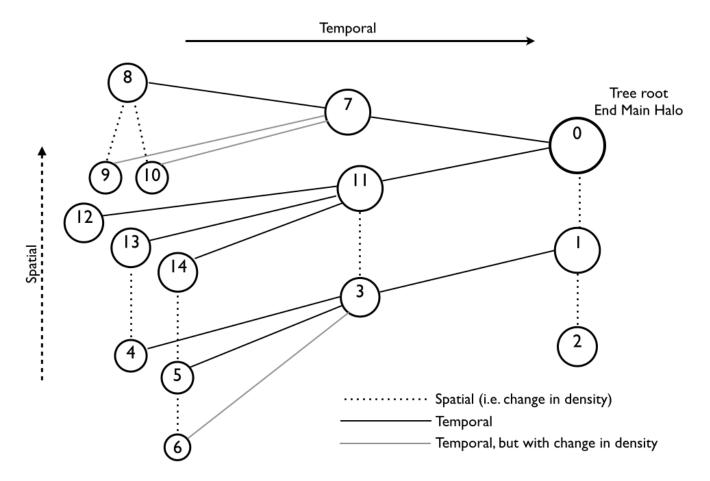


Figure A1. A test merger tree that is used for the examples in this appendix.

APPENDIX A: EXAMPLE PYTHON CODES

In this appendix we present some example PYTHON codes to search merger trees and to read/write them in HDF5 format. These routines can all be downloaded from https://bitbucket.org/ProfPAThomas/mergertree/.

The examples use the tree shown in Figure A1 as recorded in HDF5 format in test.hdf5.

A1 To read a tree written in the default format

We first present an example of how to read in data from an HDF5 file and to dump some properties to the screen. To simply the script, this example makes use of mt.py that defines a MergerTree class and some helper functions, but this is not really necessary and could easily be omitted.

```
"""readtree.py
   Example of how to read in a merger tree in HDF5 format
   Usage: python readtree.py <tree.hdf>
"""
#-----
# Imports

# The following imports the python3 print function into python2;
# It seems to be quietly ignored in python3
from __future__ import print_function
import sys
```

```
# The merger tree module contains data structures, methods and global variables
import mt
# Open file
if len(sys.argv) != 2: sys.exit("Usage: " + sys.argv[0] + " filename.hd5")
mtdata=mt.MergerTree(sys.argv[1], "r")
for (name, value) in mtdata.attrs('/'): print(name, value)
# Read in snap table
for (name, value) in mtdata.attrs("Snapshots"): print(name, value)
snap=mtdata.read_snaptable()
print('Snap =')
print('{0:>8} {1:>6} {2:>6} {3:>6}'.format(*snap.dtype.names))
for row in range(len(snap)): print('(0:>8) {1:>6.3f} {2:>6.3f} {3:>6.3f}'.format(*snap[row]))
del snap
# Read merger tree from HDF file
for (name, value) in mtdata.attrs("MergerTree"): print(name, value)
tree=mtdata.read_mergertree()
print('Tree =')
for dset in tree:
    print(dset,end=' ')
print()
for ntree in range(min(10,len(tree['HaloID']))):
    for prop in tree:
        print(tree[prop][ntree],end=' ')
    print()
del tree
#Close file
mtdata.close()
```

A2 Merger tree class and associated methods

Here is file mt.py containing the MergerTree class used in the above example.

```
print('mt usage: mt(file, mode=mode)')
# Return set of attributes associated with object
def attrs(self, object):
    return self.fid[object].attrs.items()
# Close the HDF5 file
def close(self):
   self.fid.close()
# Open the HDF5 file
def open(self, file, mode):
   self.fid = h5py.File(file, mode)
# Return a handle to the MergerTree group
def read_mergertree(self):
   return self.fid["MergerTree"]
# Return a handle to the Snapshot table
def read_snaptable(self):
   return self.fid["Snapshots/Snap"]
# Return a handle to the SnapProp table
def read_snapprop(self):
   return self.fid["Snapshots/SnapProp"]
```

A3 Tree-searching

The following example tracetree.py reads in an HDF5 file then shows how to loop over (or 'trace') a tree using a spatial and/or temporal search. It makes use of a Tree class defined in tree.py

```
# The following data set contains a simple example with both a spatial and merger trees.
infile='data/test.hdf5'
# We are going to open read only
mode='r'
#-----
# Open Merger tree file for reading
fid = h5py.File(infile, mode)
# This shows how easy it is to extract attributes from the file
for (name, value) in fid['/'].attrs.items(): print(name, value)
# Next we are going to construct a tree from the information contained in the HDF5 file
# First let's extract the number of halos
gid = fid['/MergerTree']
nHalo=gid.attrs.get('NHalo')
print('nHalo =',nHalo)
# and now the links that we want. Without the [:] we get a pointer to the array.
firstSubhalo=gid.get('FirstSubhaloIndex')[:]
neighbour=gid.get('NeighbourIndex')[:]
firstProgenitor=gid.get('FirstProgenitorIndex')[:]
nextSibling=gid.get('NextSiblingIndex')[:]
hostHalo=gid.get('HostHaloIndex')[:]
descendant=gid.get('DescendantIndex')[:]
# Initialise tree nodes...
# Trick: create an extra non-existent node to receive references to index -1 (= last index)
nodes=[tree.Tree(halo) for halo in range(nHalo+1)]
nodes[nHalo]=None
# Now we run through each of the halos extracting those pointers that we need for
# efficient tree traversal
for halo in range (nHalo):
    nodes[halo].load(nodes[firstSubhalo[halo]],
                    nodes[neighbour[halo]],
                    nodes[firstProgenitor[halo]],
                    nodes[nextSibling[halo]],
                    nodes[hostHalo[halo]],
                    nodes[descendant[halo]])
# The end main halos are those that have no Descendants and no HostHalo
# In this simple example there is only one such halo
endMainHalos=numpy.where((descendant==-1) & (hostHalo==-1))[0]
print(endMainHalos)
# Let's trace all the halos in the combined spatial and temporal tree
nodes[0].printheader()
for halo in nodes[0].next():
   print (nodes[halo])
# Here's a trace of just the spatial tree
nodes[0].printheader()
for halo in nodes[0].next('spatial'):
    print (nodes [halo])
```

```
# and here are the temporal trees for each end halo
endHalos=numpy.where(descendant==-1)[0]
for endHalo in endHalos:
   nodes[endHalo].printheader()
   for halo in nodes[endHalo].next('temporal'):
        print(nodes[halo])
```

A4 Tree-search algorithm

yield ___

We present below an example tree class with methods for generating iterators that can perform a combined (default behaviour), spatial, or temporal tree search.

```
"""tree.py
  Defines a Tree class for dealing with combined temporal and merger trees
....
#-----
# The following imports the python3 print function into python2;
# It seesm to be quietly ignored in python3
from __future__ import print_function
# In Python 3 the loops of the form
   for __ in self.something():
      yield ___
# can all be replaced by
   vield from self.something()
# which makes for much cleaner code.
#-----
class Tree:
   """Tree class for dealing with combined temporal and merger trees"""
   # Constructor: creates an empty tree node.
   def __init__(self, node):
       self.node=node
   # Load pointer arrays.
   def load(self,firstSubhalo,neighbour,firstProgenitor,nextSibling,hostHalo=-1,descendant=-1):
       self.firstSubhalo=firstSubhalo
       self.neighbour=neighbour
       self.firstProgenitor=firstProgenitor
       self.nextSibling=nextSibling
       self.hostHalo=hostHalo
       self.descendant=descendant
   # Default iterator that takes no arguments:
   # Note the asymmetry between spatial and temporal: because there is more
   # than one way to reach a node, can only iterate over one of them.
   # Because of the nature of the trees, space has to be the outer loop.
   def __next__(self):
       yield self.node
       for __ in self.nextSpatial():
          yield ___
       for __ in self.nextTemporal('temporal'):
```

```
# More general iterator method with optional argument specifying tree type:
def next(self,treeType=None):
    yield self.node
    if treeType is None:
        for __ in self.nextSpatial():
           yield ___
        for __ in self.nextTemporal('temporal'):
            yield __
    elif treeType=='spatial':
        for __ in self.nextSpatial('spatial'):
            yield ___
    elif treeType=='temporal':
        for __ in self.nextTemporal('temporal'):
            yield ___
    else:
        raise valueError('Invalid treeType for tree')
# Spatial tree search
def nextSpatial(self, treeType=None):
    if self.firstSubhalo is not None:
        for __ in self.firstSubhalo.next(treeType):
            vield
    if self.neighbour is not None:
        for __ in self.neighbour.next(treeType):
           yield ___
    #raise StopIteration()
# Temporal tree search
def nextTemporal(self,treeType=None):
    if self.firstProgenitor is not None:
        for __ in self.firstProgenitor.next(treeType):
            yield __
    if self.nextSibling is not None:
        for __ in self.nextSibling.next(treeType):
            yield ___
    #raise StopIteration()
# Printing
def printheader(self):
    print ('node, firstSubhalo, neighbour, firstProgenitor, nextSibling, hostHalo, descendant=')
def __str__(self):
   s1='-1'
   if self.firstSubhalo: s1=str(self.firstSubhalo.node)
   if self.neighbour: s2=str(self.neighbour.node)
    if self.firstProgenitor: s3=str(self.firstProgenitor.node)
   s4='-1'
   if self.nextSibling: s4=str(self.nextSibling.node)
   s5='-1'
    if self.hostHalo: s5=str(self.hostHalo.node)
   s6='-1'
   if self.descendant: s6=str(self.descendant.node)
    return str(self.node)+', '+s1+', '+s2+', '+s3+', '+s4+', '+s5+', '+s6
```

#-----

A5 To extract a tree from an HDF5 file

('neighbour','int32'),

This example, extracttree.py, reads in an HDF5 file, then extracts some data for a particular tree into a structured numpy array.

```
"""extracttree.py
  Example of how to read in a merger tree file in HDF5 format
  and to create a table containing all the data for a particular tree.
# Note: only if we pick up whole trees will the indices be guaranteed
# to be consecutive. As we only have a single tree in our test data set,
# this example takes halo 7 to be the root halo as that does have
# consecutive indices for its subtree.
# If the indices are consecutive then there is no need to use a special
# Tree class and methods to allow tree searching. However, we do first
# do this as a check.
#-----
# Imports
# The following imports the python3 print function into python2;
# It seesm to be quietly ignored in python3
from __future__ import print_function
import sys
import numpy
import h5py
# The tree module contains a class definition for a combined spatial and temporal tree
import tree
#-----
# Parameters
# The following data set contains a simple example with both a spatial and merger trees.
infile='data/test.hdf5'
# We are going to open read only
mode='r'
#-----
# Open Merger tree file for reading
fid = h5py.File(infile, mode)
# This shows how easy it is to extract attributes from the file
for (name, value) in fid['/'].attrs.items(): print(name, value)
# Let's extract the data that we want from the HDF5 file.
# Define numpy data type for the table rows
# Maybe there is a clever way to do this, but this example will just do it by hand
treedata_dtype=numpy.dtype([
       ('haloID','int64'),
       ('descendant','int32'),
       ('firstProgenitor','int32'),
       ('firstSubhalo','int32'),
       ('hostHalo','int32'),
```

```
('nextSibling','int32'),
        ('snapNum','int32'),
        ('density','f8'),
        ('mass','f8')
        1)
# First let's extract the number of halos
qid = fid['/MergerTree']
nHalo=gid.attrs.get('NHalo')
print('nHalo =',nHalo)
# and now the link that we want. Without the [:] we get a pointer to the array.
haloID=gid.get('HaloID')[:]
descendant=gid.get('DescendantIndex')[:]
firstProgenitor=gid.get('FirstProgenitorIndex')[:]
firstSubhalo=gid.get('FirstSubhaloIndex')[:]
hostHalo=gid.get('HostHaloIndex')[:]
neighbour=gid.get('NeighbourIndex')[:]
nextSibling=gid.get('NextSiblingIndex')[:]
snapNum=gid.get('Snapshot')[:]
density=gid.get('Density')[:]
mass=gid.get('Mass')[:]
# Next we are going to construct a tree from the information contained in the HDF5 file
# This is only needed for trees that are not depth-first ordered, but it's a nice example
# of how to use iterators in python anyway. It uses the Tree class in the separate tree.py file.
# Initialise tree nodes...
# Trick: create an extra non-existent node to receive references to index -1 (= last index)
nodes=[tree.Tree(halo) for halo in range(nHalo+1)]
nodes[nHalo]=None
# Now we run through each of the halos extracting those pointers that we need for
# efficient tree traversal
for halo in range (nHalo):
    nodes[halo].load(nodes[firstSubhalo[halo]],
                     nodes[neighbour[halo]],
                     nodes[firstProgenitor[halo]],
                     nodes[nextSibling[halo]],
                     nodes[hostHalo[halo]],
                     nodes[descendant[halo]])
# Let's pick a halo to act as the root of our tree.
# Ideally, we should use a full tree, but we only have one tree in this example.
# However halo 7 has consecutive indices in its subtree, so we'll use that.
root=7
nodes[root].printheader()
nTreeHalo=0
nodeMin=nodes[root].node
nodeMax=-1
for halo in nodes[root].next():
   nTreeHalo+=1
    nodeMin=min(halo,nodeMin)
   nodeMax=max(halo, nodeMax)
   print (nodes[halo])
print('nTreeHalo =',nTreeHalo)
print('nodeMin, nodeMax =', nodeMin, nodeMax)
```

```
# Now let's loop over the tree again, recording the data that we want in our table
# Create a numpty structured array to hold the table
treedata=numpy.empty(nTreeHalo,dtype=treedata_dtype)
ihalo=-1
consecutive=True
firstHalo=nodes[root].node
for halo in nodes[root].next():
   ihalo+=1
   if halo != firstHalo+ihalo: consecutive=False
    treedata[ihalo]=(haloID[halo],descendant[halo],firstProgenitor[halo],firstSubhalo[halo],
                    hostHalo[halo], neighbour[halo], nextSibling[halo],
                    snapNum[halo], density[halo], mass[halo])
print('Consecutive halos = ',consecutive)
# If we have a consecutive list of halos, adjust indices to point to the relevant location
# in our new table.
# Setting the maximum to -1 is not really necessary but helps to make things look tidier.
if consecutive:
    numpy.maximum(treedata['descendant']-nodeMin,-1,treedata['descendant']);
   numpy.maximum(treedata['firstProgenitor']-nodeMin,-1,treedata['firstProgenitor']);
    numpy.maximum(treedata['firstSubhalo']-nodeMin,-1,treedata['firstSubhalo']);
    numpy.maximum(treedata['hostHalo']-nodeMin,-1,treedata['hostHalo']);
    numpy.maximum(treedata['neighbour']-nodeMin,-1,treedata['neighbour']);
    numpy.maximum(treedata['nextSibling']-nodeMin,-1,treedata['nextSibling']);
# We have established that we have a consecutive (depth-first ordered) tree,
# so no need to bother with the Tree class again. Let's just dump the new
# properties in consecutive order as a check.
for ihalo in range(nTreeHalo):
    print(ihalo,treedata[['firstSubhalo','neighbour','firstProgenitor',
                        'nextSibling','hostHalo','descendant']][ihalo])
# Or rather more simply, but in a different order
print(treedata)
#______
```

A6 To save a tree in the default format

Finally, we have an example of how to create an HDF5 file in the correct format. Because we need some data to write out, this example also reads in data from an existing HDF5 file: in practice the data may have come from a mergertree creation algorithm.

```
import sys
import numpy as np
# The merger tree module contains data structures, methods and global variables
import mt
#-----
# Parameters
infile='data/test.hdf5'
outfile='data/dumptest_Python.hdf5'
# For the purposes of this example, we first have to read in some data.
# Actually, the following creates pointers to the data, to be read below.
mt_in=mt.MergerTree(infile, "r")
attributes = mt_in.attrs('/')
# Read in snap tables
snap_in=mt_in.read_snaptable()
snapprop_in=mt_in.read_snapprop()
snap_attributes=mt_in.attrs("Snapshots")
# Read merger tree.
tree_in=mt_in.read_mergertree()
tree_attributes=mt_in.attrs("MergerTree")
# Now we are going to create a new HDF5 file to write out the data
print('Creating output file')
mt_out=mt.MergerTree(outfile,"w")
print('File =',mt_out.fid)
# Write out the top-level attributes
print('In group', mt_out.fid.name,'attributes are:')
for (name, value) in attributes:
   print(' ',name,value)
   mt_out.fid.attrs.modify(name, value)
# Create MergerTree directory and set attributes
tree=mt_out.fid.create_group("MergerTree")
print('In group', tree.name, 'attributes are:')
for (name, value) in tree_attributes:
    print('name, value =', name, value)
    tree.attrs.modify(name, value)
# Write out merger tree datasets
print('MergerTree datasets:')
for dset in tree_in:
    # extract name, dtype and data from input dataset
   name=tree_in[dset].name
    dtype=tree_in[dset].dtype
   data=tree_in[dset][()]
   attrs=tree_in[dset].attrs.items()
    # and now recreate in the output file
    dset=tree.create_dataset(name=name, dtype=dtype, data=data)
    print(' ',name)
```

```
print('
              ', dset[0:9])
    # and set attributes
    for (name, value) in attrs:
        print(' ',name,value)
        dset.attrs.modify(name, value)
# Create Snapshot directory and set attributes
snap=mt_out.fid.create_group("Snapshots")
print('In group', snap.name, 'attributes are:')
for (name, value) in snap_attributes:
    print(' ',name,value)
    snap.attrs.modify(name, value)
# Write out Snap table
# Tables require use of a complex dtype. Fortuntately, that's already set up
# us here in the input file.
# Extract data and dtype from input file
name=snap_in.name
dtype=snap_in.dtype
nsnap=len(snap_in)
data=np.empty(nsnap,dtype=dtype)
for irow in range(nsnap): data[irow]=snap_in[irow]
# and recreate in output file
dset=tree.create_dataset(name=name,dtype=dtype,data=data)
print('Snap table:')
print(' name =', dset.name)
print(' dtype =',dset.dtype)
print(' data =', dset[:])
# Write out SnapProp table
# us here in the input file.
# Extract data and dtype from input file
name=snapprop_in.name
dtype=snapprop_in.dtype
nsnapprop=len(snapprop_in)
data=np.empty(nsnapprop,dtype=dtype)
for irow in range(nsnapprop): data[irow]=snapprop_in[irow]
# Rename the Units property to lower case (for consistency).
# Cannot rename in place: have to make a copy of both dtype and data.
temp=dtype.___repr___() [6:-1]
temp=temp.replace("Units", "units")
dtypenew=np.dtype(eval(temp))
print('dtypenew=',dtypenew)
datanew=np.empty(nsnapprop,dtype=dtypenew)
for irow in range(nsnapprop): datanew[irow]=data[irow]
# and recreate in output file
dset=tree.create_dataset(name=name,dtype=dtypenew,data=datanew)
print('SnapProp table:')
print(' name =', dset.name)
print(' dtype =',dset.dtype)
print(' data =', dset[:])
# The output file is not yet a complete examle of the merger tree data
# format, but hopefuly that is enough to illustrate how do do things.
# Close the files
mt in.close()
```

		Merger Tree Data Format
<pre>mt_out.close()</pre>		